(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
11 December 2003 (11.12.2003)

PCT

(10) International Publication Number
WO 03/101658 A1

(51) International Patent Classification[7]: B23K 9/095, 9/173

(21) International Application Number: PCT/AU03/00674

(22) International Filing Date: 30 May 2003 (30.05.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
PS 2740 3 June 2002 (03.06.2002) AU

(71) Applicant *(for all designated States except US)*: **UNIVERSITY OF WOLLONGONG** [AU/AU]; Northfields Avenue, Wollongong, New South Wales 2522 (AU).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **NORRISH, John** [AU/AU]; 10 Godolphin Street, Bulli, New South Wales 2516 (AU). **COOK, Christopher, David** [AU/AU]; 4 Haig Street, Wombarra, New South Wales 2515 (AU). **CUIURI, Dominic** [AU/AU]; 149 Derribong Drive, Cordeaux Heights, New South Wales 2526 (AU). **DI PIETRO, Paul** [AU/AU]; 35 Charles Road, Fernhill, New South Wales 2519 (AU). **DEAN, Gary** [AU/AU]; 78 Hillside Drive, Albion Park, New South Wales 2527 (AU).

(74) Agent: **PHILLIPS ORMONDE & FITZPATRICK**; 367 Collins Street, Melbourne, Victoria 3000 (AU).

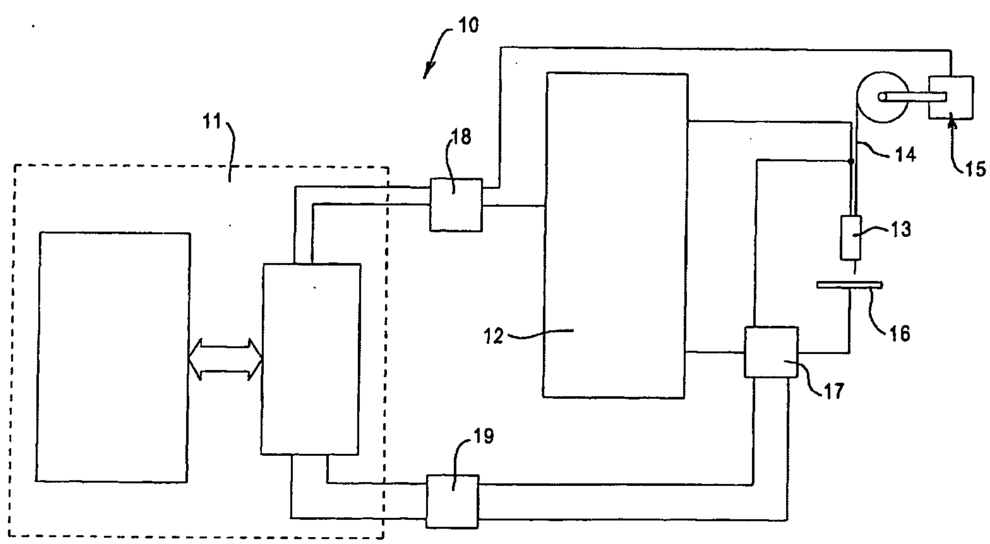
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: CONTROL METHOD AND SYSTEM FOR METAL ARC WELDING



(57) Abstract: A method of controlling an arc welding system during a welding process is disclosed. The welding process has a plurality of welding cycles in which a consumable electrode (14) is advanced towards a workpiece (16). The method includes dynamically regulating a rate of advancement and instantaneous melt rate of the electrode during each welding cycle in response to predetermined events occurring during the welding process. The melt rate may be coordinated with the rate of advancement of the electrode to provide a wide range of stable deposition rates with a shielding gas such as CO_2. An arc welding system for carrying out the method is also disclosed.

WO 03/101658 A1

CONTROL METHOD AND SYSTEM FOR METAL ARC WELDING

FIELD OF THE INVENTION

The present invention relates generally to welding and more specifically to control methods and systems for use in gas metal arc welding (GMAW).

BACKGROUND OF THE INVENTION

In a typical GMAW process, a welding circuit is established which includes a consumable electrode, a workpiece and a power source. The electrode is generally a solid wire and not only conducts the electric current that sustains the arc, but also melts and supplies filler material into the joint. A shielding gas such as argon or carbon dioxide (CO_2) or blends of argon and helium with CO_2 and/or oxygen may be supplied during the welding process to support the arc and prevent the molten metal reacting with oxygen and nitrogen in ambient air.

A GMAW process can be made to operate reliably over a wide range of deposition rates when used with an argon or argon-helium based shielding gas. At low deposition (or wire feed) rates, current densities in the wire electrode are low, and the process operates in short-circuit transfer mode. In this mode, the molten droplet formed at the end of the electrode regularly touches the weld pool, and metal transfer is achieved through a combination of surface tension and electromagnetic forces. This mode can be made to operate very stably with correct selection of key process parameters.

As the wire feed rate is increased, the current density must also increase so that the melting rate matches the feed rate. For mean currents of approximately 170A to 200A for 0.9mm diameter wire, the process operates in a globular transfer mode. This mode is characterised by large droplets being detached by a combination of gravity and electromagnetic forces at irregular intervals. The irregular metal transfer results in poor bead appearance and low operator appeal. In these current ranges, the GMAW process is preferably operated in pulsed spray transfer, an open-arc process

where the metal transfer is regular and can be precisely controlled by the current wave form. A droplet of consistent size is propelled across the arc at regular intervals with minimal spatter to produce a smooth weld bead of intermediate size.

Above approximately 200A for 0.9mm wire, the process transits to spray transfer mode. In this mode, fine droplets having a diameter less than that of the electrode are propelled from the electrode towards the weld pool at a high speed across the open arc. As current is increased, the droplet becomes finer and the electrode end becomes more tapered. The constant metal transfer produces a smooth weld bead. The high current produces high heat input and relatively wide bead. Large fusion areas and deep penetration can also be achieved if the travel speed is high enough to avoid "puddling", but without producing undercut. Due to the large, highly liquid weld pool, the positional capability of this mode is mostly limited to down hand. At very high currents (above 400A), and where the electrode stick out length is sufficiently long, rotating arc transfer can be produced. Under these conditions, it is thought that the resistive preheating of the electrode is sufficiently high to soften it to a point where it is rotated by the non axial arc forces. If very high deposition rates are required, then a larger electrode is used in spray mode at lower wire feed rates.

Due to the availability of a number of distinct operating modes as mentioned above, the argon-based GMAW process offers the ability to operate over a very wide range of deposition rates for a given electrode size. As such it has been widely used in the welding industry.

The major disadvantage of argon is its comparatively high cost of production, compared to CO_2. As CO_2 is a by-product of processing such as brewing, it is relatively inexpensive since low temperature distillation equipment is not required. However there are a number of limitations which need to be overcome to using CO_2-shielded GMAW for high volume production welding.

The most significant difference between GMAW processes using CO_2, and argon based shielding gas is that the CO_2 process does not exhibit a spray transfer mode. For low currents (less than 170A for 0.9mm wire) the

CO_2 process operates in dip transfer mode. The overall behaviour is similar to that for argon, but spatter levels tend to be higher and the bead finish is not smooth.

While it is possible to deposit a weld bead using globular transfer by increasing the current, the resulting weld bead has a poor appearance, arc stability is also poor, and spatter is very high.

SUMMARY OF THE INVENTION

An aim of the invention is to provide improved methods and systems for controlling a welding process so as to produce good quality welds at high deposition rates. A particular aim of the invention is to increase the deposition rates which can be achieved using CO_2 or mixed shielding gases whilst maintaining good weld quality.

According to one aspect of the present invention there is provided a method of controlling an arc welding system during a welding process having a plurality of welding cycles in which a consumable electrode is advanced towards a workpiece, said method including dynamically regulating a rate of advancement and instantaneous melt rate of said electrode during each welding cycle in response to predetermined events occuring during said welding process.

In one form, the invention may be directed to a method of controlling an arc welding process having a welding cycle in which a consumable electrode is advanced towards a workpiece, where both the instantaneous melting rate of the electrode and the rate of advancement of that electrode are controlled and regulated during the welding cycle. The invention is also directed to a welding system that allows these welding parameters to be controlled and regulated, and a controller for use in that welding system.

A method of controlling an arc welding process according to the present invention has substantial benefit. In particular, this method can be employed to significantly improve the deposition rate whilst maintaining good weld quality. Specifically, it enables the parameters of the welding process to be more finely controlled allowing better control over the growth of the droplet and transfer of that droplet to the workpiece.

In a particularly preferred form, the instantaneous melting rate of the electrode may be controlled by controlling the current waveform generated by the power source. To enable the current to be appropriately controlled, the power source needs to have an adequate response time. Current response rates of 250 A/ms (Amperes per millisecond) have been found to be suitable, but rates above 400 A/ms are preferred.

In one form, a switching power source which incorporates a switching circuit is used to allow control of the current waveform. In an alternative arrangement, a linear power source is used where the output current is regulated through a linear output stage.

In a preferred form, to control and regulate the rate of advancement of the electrode during the welding cycle, an improved electrode (or wire) feed unit is employed in the welding process. In a particularly preferred form, the wire feed unit is able to cause the electrode to reverse. This again provides more opportunity to better control the welding process to allow for good quality welds to be made at high deposition rates.

Similar to the requirement for the power source, the response time of the wire feed unit to instructions to change its feed rate must be fast enough to enable it to be beneficially used in the welding process. Tests have shown that the process operates well if the time taken to stop a 0.9mm diameter electrode from 40 metres per minute is approximately 2.1 ms, while the time taken to accelerate the same electrode from 40 metres per minute reverse to 40 metres per minute forward is approximately 3.8 ms.

In one form, a controller is used to co-ordinate the control of the rate of advancement of the electrode and the instantaneous melt rate. In a preferred form, the controller monitors the welding cycle to establish when various events occur in the welding cycle and then regulates the rate of advancement and the melting rate in response thereto.

In a preferred form, variables defining the instantaneous melt rate and the rate of advancement of the electrode in the welding cycle are entered into the controller. Each of these variables are referenced to particular stages in the welding cycle so that the controller is able to adjust these parameters during the welding cycle.

In one form, the controller samples conditions during the welding process at regular intervals (say 40 microseconds) and registers the feedback voltage to establish in real time, the occurrence of predetermined events in the welding cycle so as to allow the controller to establish the present stage of the welding cycle. The controller conducts processing steps using information gained from the feedback voltage and from the entered variables to determine whether the rate of advancement or the instantaneous melt rate of the electrode need to be changed and then issues updated reference signals. This updated reference signal may maintain the status quo, or change the parameters if required. In the arrangement where the rate of advancement is determined by the wire feed unit, then the updated reference signal is used to control that unit. Similarly where the instantaneous melting rate of the electrode is controlled by the current waveform generated by the power source, then the reference signal is used to establish the appropriate level of that current waveform.

Controlling both the rate of advancement and the instantaneous melt rate of the electrode can significantly increase the deposition rates in the welding process. In particular, it can allow for faster and more controlled growth of the molten droplet by increasing the wire feed rate and current rate during droplet growth, and can provide more controlled transfer of the droplet to the workpiece, through a reduction in both these parameters.

In a particularly preferred form, the invention can significantly increase deposition rates of a welding process operating in a dip transfer mode. In that mode, the welding cycle comprises an arcing phase where the electrode is spaced from the workpiece and an arc is generated across the space, and a short circuit phase where the electrode is in contact with the workpiece. The welding cycle changes from the arcing phase to the short circuit phase on contact of the molten droplet with the workpiece, and changes from the short circuit phase to the arcing phase after rupturing of a bridge of molten material formed between the electrode and the workpiece.

Being able to substantially increase the deposition rates in dip transfer mode has significant benefits to CO_2-shielded welding processes where it is required to operate in that mode to provide satisfactory weld quality. Using

the techniques of the invention the inventors have found that it is possible to at least double the deposition rate for a CO_2 process operating in dip transfer mode as compared to conventional processes without unduly affecting weld quality.

In a conventional CO_2 process operating in the dip transfer mode, the diameter of the droplet grown is generally less than 1.5 times the electrode diameter, and commonly less than the electrode diameter. Increasing the wire feed rate and the current level in an attempt to increase deposition rate causes the CO_2 process to transit to globular mode, which is an open arc process. Observations of the process has shown that large droplets having a diameter much larger than the electrode diameter form at the tip of the electrode. While it is possible to deposit a weld bead using a globular transfer in CO_2, the resulting weld bead has a poor appearance, arc stability is also poor and spatter is very high. Arc force tends to push the droplet upwards and away from the weld pool, leading to the description of "repelled globular transfer". The large droplets are detached by gravity at low frequencies (less than 10Hz).

The inventors have found that by controlling the rate of advancement of the electrode and the instantaneous melting rate of the electrode, it is possible to both grow the droplet on the electrode quickly to a size which is significantly larger than the diameter of the electrode, yet still cause the welding process to operate in a short circuit mode while avoiding droplet repulsion and excessive production of spatter. In this way, the operating range of the short circuiting transfer mode is extended and covers a higher range of deposition rates which would normally be associated with the use of either globular or pulsed spray transfer modes, but without incurring the associated disadvantages of these modes in CO_2.

The size of the droplet grown on the electrode may vary significantly. However, preferably the droplet diameter is in the order of 1.4mm to 2.5mm for a 0.9mm diameter wire. The size of the droplet that can be grown in any given time is limited as there exists a relationship between the arcing pulse current I_p and pulse time T_p which droplets will be produced and ejected from the electrode. Since free flight transfer is to be avoided in the short circuit

transfer in CO_2, it is important that the conditions of the welding process (particularly the pulse current and pulse time) are set so that there is no droplet detachment during the arcing phase.

The inventors have found that the relationship between the arcing pulse current I_p and the pulse time T_p is influenced by changes in electrode preheating. Accordingly, in addition to controlling the rate of advancement and the instantaneous melt rate of the electrode, the process may regulate other factors such as those to influence electrode preheating.

One parameter of the welding process which has a direct influence on electrode preheating is the contact tip to workpiece distance (CTWD).

The inventors have found that using high CTWD can further significantly increase the deposition rates whilst maintaining good weld quality. An advantage of a high CTWD, is that it produces electrode resistive preheating as there is additional time that the electrode material is exposed to current flow prior to entering the welding arc zone. With the changes in electrode preheating, the electrodes are able to be subjected to higher melting rates without droplet detachment. Further, an increase in the CTWD effectively reduces the magnitude of the current required to produce a given droplet in a given time, and simultaneously reduces the arc force acting on the weld pool.

In conventional CO_2 welding, the CTWD is in the order of 10mm to 20mm. Preferably using the process of the present invention, the CTWD is in the order of 10mm to 50mm.

As the deposition rate is increased by being able to grow larger droplets more quickly, it is desirable in a welding application to increase the welding travel speed rather than produce larger weld beads at a slow travel speed. If the droplet transfer rate is too low for high travel speeds, then the weld bead will become "lumpy" or even discontinuous. Therefore, in a preferred form the droplet transfer rate is greater than 30Hz and more preferably is greater than 45Hz.

In a preferred form, during the arcing phase, the instantaneous melting rate and the rate of advancement are higher than in conventional CO_2 process so as to grow the droplet quickly and to a size which is larger

than the electrode diameter. The parameters of the process are then changed to ensure that a short circuit will initially occur by increasing the rate of advancement to force the droplet into the workpiece and further that the short circuit will then rupture, by subsequently reducing the rate of advancement of the electrode.

In a particularly preferred form, the electrode is caused to reverse during the short circuit phase to prevent short circuit stubbing of the electrode tip into the weld pool. When a constant wire feed speed system is used at increasingly high speed, it becomes quite difficult (and eventually impossible) to rupture the short circuit. Significantly greater short circuiting currents are required, because the length of the molten bridge changes during the duration of the short. For example, at 18 metres/minute the bridge length will reduce by 1.2mm during a 4 millisecond short. By reducing or reversing the electrode feed during the short circuit, this mechanism for stubbing is avoided. In addition, the reversal of the electrode ensures that the short circuit can be interrupted with lower current than that necessary for a constant wire feed speed system.

In a further form, the invention relates to a method of controlling an arc welding system using a shielding gas and operating in a dip transfer mode, the welding system including a power source and a consumable electrode which in use is operative to be advanced into contact with a workpiece, the welding system being operative to create a welding circuit which is energised by the power source and which has a welding cycle including an arcing phase where the electrode is spaced from the workpiece and an arc is generated across the space, the arc being operative to form a molten droplet on the end of the electrode, and a short circuit phase where the electrode is in contact with the workpiece, the welding cycle changing from the arcing phase to the short circuit phase on contact of the molten droplet with the workpiece, and changing from the short circuit phase to the arcing phase after rupturing of a bridge of molten material formed between the electrode and the workpiece, the method including the steps of:

(i) conditioning the welding system to form a molten droplet on the electrode end during the arcing phase which has a diameter greater than the diameter of the electrode, and

(ii) causing the droplet to detach from the electrode after the molten droplet has come into contact with the workpiece to thereby ensure a short circuit and arcing phase occurs in the welding cycle.

In preferred embodiments of the invention the molten droplet formed on the end of the electrode during the arcing phase may be between 1.1 to 2.3 times the diameter of the electrode.

In a preferred embodiment according to a further form of the invention, the duration of the arcing phase is within the range of 5 milliseconds to 50 milliseconds, and the short circuit phase is within the range of 2.5 milliseconds to 10 milliseconds.

This further form of the invention is ideally suited to be used in conjunction with the first form of the invention to adjust the parameters of the welding process to appropriately condition the welding system.

Preferably, the average rate of advancement of the electrode towards the workpiece is greater in the arcing phase than in the short circuit phase. Further, preferably the welding current is controlled so that average current rate is greater in the arcing phase than in the short circuit phase. Controlling both these parameters allows the droplet to be grown quickly to the desired size in the arcing phase.

Preferably the method includes controlling the current during the welding cycle so that the droplet contacts the workpiece to cause the short circuit at reduced current to thereby minimise spatter created by the repulsion forces at the contact point.

In yet a further preferred form, the rate of advancement of the electrode towards the workpiece is reduced substantially during the short circuit phase so as to ensure the successful termination of the short circuit. In a particularly preferred form, the electrode feed is caused to reverse during the short circuit phase.

In yet a further preferred form, a current pulse is applied during the short circuit phase to reduce the time taken to transfer the molten metal from

the droplet to the workpiece. Preferably the short circuit current pulse is controlled in the welding system so that the end of the pulse occurs before the completion of the short circuit phase.

According to a further aspect of the present invention there is provided an arc welding system including a power source, a control unit and means for advancing a consumable electrode towards a workpiece during a welding process, said consumable electrode being energized by said power source to cause said electrode to supply molten material to said workpiece, wherein said means for advancing is controlled by said control unit to dynamically regulate a rate of advancement of said electrode in response to predetermined events occurring during said welding process.

BRIEF DESCRIPTION OF THE DRAWINGS

It is convenient to hereinafter describe an embodiment of the present invention with reference to the accompanying drawings. It is to be appreciated that the particularity of the drawings and the related description should be understand as not superseding the generality of the preceding broad description of the invention.

In the drawings:

Figure 1 is a block diagram of a welding system;

Figure 2 is a detailed schematic view of a reversing wire feed unit used in the system of Figure 1;

Figure 3 is a typical user interface screen for the controller of the welding system of Figure 1;

Figure 4 is a typical waveform for current, wire feed speed and welding voltage used in the welding system of Figure 1;

Figure 5 are photographs of weld beads (0.9 mm wire) using the system of Figure 1;

Figure 6 is an I_p -T_p relationship for 0.9 mm electrode in CO_2; and

Figure 7 is an I_p -T_p relationship for 1.2 mm electrode in CO_2.

DETAILED DESCRIPTION OF THE DRAWINGS

Turning firstly to Figure 1, a welding system 10 is illustrated which includes a control unit 11, welding power source 12 which is connected to a welding torch 13. A consumable metal electrode 14 is fed into the welding torch 13 under operation of a reversible wire feed unit 15. The consumable electrode is energised by the power source 12 which causes the electrode to melt to thereby supply molten metal to a workpiece 16.

The welding system also include a feedback unit 17 which is connected between the workpiece 15 and the power source 12. The feedback unit 17 supplies voltage and current feedback to the control unit 11. The system also includes a signal reference unit 18 and a feedback isolation unit 19 to provide integrity to the welding system. The control unit 11 is able to supply through the signal reference unit 18 reference signals to both the power source 12 and the wire feed unit 15 so as to control the functions of those units as will be described in more detail below.

Figure 2 illustrates the reversing wire feed unit 15 in more detail. The unit 15 includes a wire feed roll 20 which is located close to the contact tip (ie the outer tip of the electrode) and is driven by a drive motor 21 located approximate to the axis of the roll 20. The drive motor is a commercially available low inertia permanent magnet AC servomotor, which in turn is controlled by a microprocessor based variable speed drive 22. Baldor servomotor BSM63A-375AA and matching drive unit FD2A07TR-RN20 are examples of suitable equipment. The distance between the wire feed roll and the contact tip is minimised to avoid wire "springing" effects and ensure that any movement at the tip of the electrode corresponds to the controlled motion at the feed roll. The time taken to stop 0.9 mm diameter wire from full speed (40 metres per minute) is approximately 2.1 ms, while the time taken to accelerate wire from 40 metres per minute reverse to 40 metres per minute forward is approximately 3.8 ms.

The power source 12 consists of a switching-type converter circuit to supply the desired welding current during the arcing phase at high efficiency, and an independent parallel-connected linear output stage to supply current at high response rate during the short-circuiting phase. The use of the linear

output stage ensures that the current can be rapidly reduced through the short-circuited output, a function that cannot be performed by a conventional switching-type converter circuit without resorting to use of secondary switching transistors, such as taught by Nakanishi et al in U.S. patent 4,544,826. The introduction of secondary switching transistors creates additional conduction losses during the arcing phase. Although the linear output stage is more inefficient than the switching-type converter, it is only operated during the short circuiting phase, which is typically less than 25% of the total welding cycle. In addition, the current needs to be supplied at a lower voltage than that developed during the arcing phase, so equipment rating and electrical losses can be minimised.

The control unit 11 comprises a computer interfaced with a digital signal processor (DSP). The DSP is used to control the current reference signal to the power source 12, as well as the wire feed reference signal to the wire feed unit 15. The DSP also monitors in real time the voltage and current feedback. The DSP is housed in a standard desktop personal computer. The DSP card has on board analogue and digital input and output points, to interface with external equipment. The operation of this card is independent of the PC operating system, allowing for uninterrupted real time control of the welding process. Control of the DSP is through custom developed software especially for the welding application. The control unit 11 does not need to comprise a computer with a compatible DSP, all the functions of the controlled computer in the DSP can be performed using a microprocessor or electronic hardware system.

In operation, the DSP is designed to sample conditions every 40 microseconds. During sampling, electronic circuitry interrupts the DSP programme. The DSP then registers the feedback voltage (and current if required), conducts processing steps and issues an update current reference signal to the power source and an updated wire feed reference signal. The current reference signal controls the current level outputted by the power source which in turn determines the instantaneous melt rate of the electrode 14 at its contact tip 23. The control unit 11 also provides a wire feed reference signal to the speed drive 22 of the wire feed unit 15 which in

turn controls the AC servomotor to control the rate of advancement of the electrode towards the workpiece 16.

Numerous variables are entered into the control unit 11 via a user interface screen 24 shown in Figure 3. These variables 25 establish the desired current levels and the wire feed rate as well as other parameters in the welding process as discussed in more detail below with reference to Figure 4.

The control method controls the current waveform to control the instantaneous melting rate of the electrode and the instantaneous wire feed rate in response to events in the process, as signaled by the voltage feedback. Typical reference waveforms for current and wire feed rate, as well as welding voltage, are shown in Figure 4. The shape of the voltage waveform is typical of that observed during tests. The figure depicts one complete metal transfer cycle in the process. The descriptions of key parameters (such as "Iarc_max") are included in the figure, as these will be used in description below.

The process is considered to proceed in several distinct stages. Stages 2, 3 and 4 constitute the short-circuiting period, when the droplet forms a bridge connecting the electrode tip to the weld pool. Stages 5, 6 and 1 constitute the arcing period, when the droplet is formed at the tip of the electrode, and the arc contributes to workpiece heating. The short circuit period is typically 2.5 to 6 milliseconds in duration, while the arcing period lasts typically 5 to 50 milliseconds. The typical range of dipping frequency is 20 to 100Hz.

Stage 6 has the longest duration, and contributes the greatest amount of heat input to the workpiece. The wire is fed forwards into the process at the nominal rate. The current is chosen to balance the feeding rate with the melting rate, so that as the droplet is formed on the tip of the electrode, the arc length decreases slowly but is sufficient to avoid an accidental short circuit. The change in arc length at a constant current is reflected in the voltage waveform. For a 0.9mm electrode feeding at 20 m/min (790 in/min) with a CTWD (contact tip to workpiece distance) of 12mm, the balance current is approximately 325A. This current is maintained for the appropriate

time, and this approximately determines the droplet size and dipping frequency. For controlling purposes, the process is then considered to enter stage 1, although the process continues to arc.

In stage 1, the current is rapidly reduced ($Iarc\_ramp_2$) to a background level (I_backgr, say 25A), and the wire feed rate is increased to a higher level (note that WFR_min is not necessarily less than WFR_max or WFR_med; the nomenclature of WFR_*min* coincides with Iarc_*min*). These steps are intended to promote the onset of the next short circuit. The reduction in arc force also removes weld pool depression, which should assist in reducing the duration of this stage. It is desirable to minimise the duration of this stage, because there is very little contribution to heat input at the background current. It is also desirable to make the short circuit occur at low current, to minimise ball repulsion spatter. Regular short circuiting at 300A would produce unacceptably high spatter levels. Current Iarc_min is less than 125A, and generally around 80A. Unlike stage 6, the duration of stage 1 is not directly controlled, although it is influenced by Iarc_min, Iarc_ramp2, arc length and WFR_min. Stage 1 duration is dependent on the behaviour of the process, so the control method is inherently adaptive to the process. When the short circuit is detected (voltage drops below V_{sc} in Figure 3), the stage 2 period begins. For a fixed duration of T_wetting (usually 0.5ms), the current is maintained at background level (approximately 20 Amperes) to promote wetting of the droplet into the weld pool and to avoid repulsion. At the beginning of this stage, the wire feeding is reversed. As stated previously, the mechanism requires 2ms to stop the electrode, so there is no chance of the short circuit being broken by taking this action.

In stage 3, the current is allowed to increase to value Isc_max for specified time Tsc_pulse, producing an electromagnetic pinch force which pumps the molten metal from the droplet into the weld pool. Simultaneously, the tip of the electrode comes to a halt and then begins to reverse away from the weld pool. This is vital to avoiding stubbing at high wire feed rates. The purpose of the current pulse during the short circuit is to appreciably reduce the duration of the metal transfer, compared to the time that would be required if no current were applied, and transfer would occur solely under the

influence of surface tension forces. The duration of the pulse is specified so that the current pulse is removed before the short circuit ruptures in stage 4. In this way, the rupturing of the short circuit occurs at reduced current to minimise spatter and weld pool disturbance. The value of Tsc_pulse can be automatically altered by the controller, based on the performance of the process in previous weld cycles, so that the short circuit rupture does not occur during stage 3. As described earlier, the power source is designed so that a rapid current turnoff into a short circuit can be achieved within a suitably low time (typically less than 350 microseconds, and preferably less than 100 microseconds).

During stage 4, the current is reduced to the background level and the short circuit rupture occurs at reduced current. The reverse motion of the wire guarantees this event. Another advantage of the reversal is that a lower maximum short-circuiting current (Isc_max) can be used, compared to the value needed for constant wire speed systems to ensure that a timely rupture occurs. A further advantage is that the onset of the short circuit rupture does not need to be predicted (as taught in U.S. patents 4,546,234 and 4,954,691) since the short circuiting current is already low enough in stage 4 to avoid spatter and weld pool disturbance. Alternatively stage 4 can be removed from the control method and the duration of stage 3 extended until short circuit rupture (as taught in US patent 6,512,200). When the voltage feedback exceeds V_{arc}, the short circuit neck has ruptured and arcing has commenced. As for stage 1, the exact duration of stage 4 is determined by the process, although the control parameters do influence the average value of these times.

The control parameters of stage 5 produce the initial conditions for the arcing period. The electrode is brought to a standstill, and the current can be increased to a level higher (Iarc_max) than the nominal arcing current (Iarc_med) of stage 6. This establishes the initial arc length, which must be long enough to avoid premature short circuiting due to oscillatory motion of the weld pool. The ability to hold the electrode stationary while extending the arc length means that the stage 5 current does not need to be much greater than the nominal arcing current. This avoids excessive weld pool

depression, disturbance, spatter and possible excessive arc gouging of the workpiece which would otherwise occur for systems using constant wire feed speed. Note that the electrode holding time T_dwell can be less than Tarc_max, and can also be extended into stage 6 if necessary. The wire feed speed during stage 5 can be higher than the value in stage 6. In some situations, it is desirable to promote very rapid droplet growth while maintaining a constant arc length at high current, since there is less chance of droplet detachment from the electrode when it is small. If the high current does not cause molten metal to be ejected from the weld pool, then the average melting rate (hence deposition rate) can be increased.

EXAMPLES

A range of experiments have been carried out using 0.9mm and 1.2mm diameter steel electrodes. The welding parameters were progressively adjusted to produce the highest deposition rate at certain CTWD values, while maintaining low spatter, high stability and good bead appearance. The results are summarised as follows:

Table 1 Summary of maximum deposition rates

Wire type AWS A5.18	**CTWD** mm	**Avg wire feed rate** m/min [in/min]	**Deposition rate** kg/hr [lb/hr]	**Mean current** Amperes
0.9mm ER70S-6	12	17.5 [690]	5.2 [11.1]	250
0.9mm ER70S-6	35	21.0 [830]	6.3 [13.4]	180
1.2mm ER70S-4	16	10.0 [395]	5.3 [11.3]	290
1.2mm ER70S-4	35	13.5 [530]	7.1 [15.1]	245

The welding parameters and weld statistics for selected welds in each of the four and additional categories are listed below in Examples 1 to 6. The

experiments conducted have been aimed at establishing the limits of the control method described above, using the equipment described. It should be noted that the welds performed at these deposition rates shown in Table 1 are achieved using conditions which were consistently repeatable, and not at the edge of the performance envelope. For example, the 1.2mm ER70S-4 electrode at a CTWD of 35mm has been operated at 16.0 m/min (refer to Example 4). However, at this deposition rate the spatter level was considered unacceptably high (visual assessment), although the bead quality had not significantly deteriorated in comparison to that at 13.5 m/min. It should also be noted that for deposition rates below those specified in Table 1, it is a straightforward exercise to find parameter sets that produce excellent welds of high stability and low spatter. The parameters become progressively more difficult to select as the limits of the process are approached.

In analysing the welding statistics provided in Examples 1 to 6, it is possible to determine the average droplet size formed on the electrode during the weld runs using the following equation:

$$d_{drop} \approx \sqrt[3]{1.5\, d_e^2 \frac{WFR_{avg}}{f_{sc}}}$$

where: d_{drop} is the approximate droplet diameter in millimetres
d_e is the electrode diameter in millimetres
WFR_{avg} is the average wire feed rate in millimetres per second
f_{sc} is the average short circuiting frequency per second

All welds in the examples had a diameter which was significantly greater than the diameter of the electrode. Specifically, the average droplet size in the examples was in the range of 1.43 to 2.45 times the diameter of the electrode. This droplet growth is achieved quickly, with the dipping time frequencies being in the range of 33 Hz to 96 Hz. Further, the parameters of the welding process were controlled so that inadvertent droplet detachment did not occur as disclosed in more detail below.

Example 1
Statistics and parameter settings for selected welds:
0.9mm AWS A5.18 ER70S-6 electrode, 12mm CTWD, CO_2 shielding.

Table A3-1: Weld Statistics

File / Weld	Avg wire feed rate (m/min)	Short-cct frequency (Hz)	Stability index	Mean current (Amps)	RMS current (Amps)	Mean voltage (Volts)	Travel speed (mm/min)	Heat input (J/mm)	Mean dip time (ms)
W1115	17.1	48	0.84	194	235	27.4	390	911	3.83
W1120	18.7	42	0.75	264	286	25.6	390	1127	4.52
W1130	17.2	62	0.84	246	272	25.4	390	1106	2.92
W1300	17.4	54	0.87	233	264	27.7	390	1146	2.99

Table A3-2: Welding Parameters 1

File / Weld	WFR_max (m/min)	WFR_med (m/min)	WFR_min (m/min)	WFR_rev (m/min)	T_dwell (ms)	Iarc_max (Amps)	Tarc_max (ms)	Iarc_ramp1 (Amps/ms)	Iarc_med (Amps)
W1115	25	25	35	20	3.0	350	1.5	150	350
W1120	30	30	40	20	2.0	350	10.0	50	250
W1130	35	35	20	30	1.0	350	7.0	100	250
W1300	35	35	20	35	1.5	375	5.0	100	275

Table A3-3: Welding Parameters 2

File / Weld	Tarc_med (ms)	Iarc_ramp2 (Amps/ms)	Iarc_min (Amps)	I_backgr (Amps)	T_wetting (ms)	Isc_max (Amps)	Isc_ramp (Amps/ms)	V_sc (Volts)	V_arc (Volts)
W1115	5.0	150	80	20	0.5	350	150	8.0	18.0
W1120	5.0	50	80	20	0.5	350	150	8.0	18.0
W1130	2.0	100	125	20	0.5	350	150	8.0	18.0
W1300	5.0	100	80	20	0.5	350	150	8.0	18.0

Table A3-4: Comments

File / Weld	Comments
W1115	Low spatter, especially for the average wire feed rate.
W1120	Spatter higher than w1115. 350A/10ms seems limit for not causing pulse detachment of droplet during arcing.
W1130	Nice bead, lower spatter and s/c time due to higher reverse wire feed speed.
W1300	Nice bead, low to medium spatter. Increasing WFR_max causes stubbing & high spatter.

Example 2

Statistics and parameter settings for selected welds:

0.9mm AWS A5.18 ER70S-6 electrode, 35mm CTWD, CO_2 shielding.

Table A4-1: Weld Statistics

File / Weld	Avg wire feed rate (m/min)	Short-cct frequency (Hz)	Stability Index	Mean current (Amps)	RMS current (Amps)	Mean voltage (Volts)	Travel speed (mm/min)	Heat input (J/mm)	Mean dip time (ms)
W1200	18.6	43	0.80	171	184	30.4	390	844	4.37
W1205	19.7	50	0.87	175	190	29.2	390	845	4.26
W1210	21.0	48	0.86	181	195	30.3	390	905	4.41
W1215	19.9	46	0.94	178	190	30.6	390	889	4.43

Table A4-2: Welding Parameters 1

File / Weld	WFR_max (m/min)	WFR_med (m/min)	WFR_min (m/min)	WFR_rev (m/min)	T_dwell (ms)	Iarc_max (Amps)	Tarc_max (ms)	Iarc_ramp1 (Amps/ms)	Iarc_med (Amps)
W1200	30	30	40	30	1.5	250	4.0	100	175
W1205	35	35	40	30	1.5	240	4.0	100	210
W1210	40	40	40	35	1.5	240	4.0	100	210
W1215	35	35	40	30	1.5	250	4.0	100	175

Table A4-3: Welding Parameters 2

File / Weld	Tarc_med (ms)	Iarc_ramp2 (Amps/ms)	Iarc_min (Amps)	I_backgr (Amps)	T_wetting (ms)	Isc_max (Amps)	Isc_ramp (Amps/ms)	V_sc (Volts)	V_arc (Volts)
W1200	10.0	100	80	20	0.5	250	150	8.0	18.0
W1205	6.0	100	80	20	0.5	250	150	8.0	18.0
W1210	7.5	100	80	20	0.5	250	150	8.0	18.0
W1215	10.0	100	80	20	0.5	250	150	8.0	18.0

Table A4-4: Comments

File / Weld	Comments
W1200	Nice running condition, low spatter weld. Arcing times distribution slightly bimodal.
W1205	Very low spatter weld, very good condition.
W1210	Very low spatter weld, very good condition.
W1215	Excellent condition, low spatter weld.

Example 3
Statistics and parameter settings for selected welds:
1.2mm AWS A5.18 ER70S-4 electrode, 16mm CTWD, CO_2 shielding.

Table A5-1: Weld Statistics

File / Weld	Avg wire feed rate (m/min)	Short-cct frequency (Hz)	Stability index	Mean current (Amps)	RMS current (Amps)	Mean voltage (Volts)	Travel speed (mm/min)	Heat input (J/mm)	Mean dip time (ms)
W9050	8.1	48	0.84	253	279	24.8	390	1103	3.65
W9065	9.8	42	0.80	290	323	23.6	390	1228	5.40
W9070	10.0	45	0.81	290	328	23.1	390	1229	5.45
W9075	10.0	36	0.83	281	328	25.1	390	1276	5.25
W9085	10.2	39	0.77	285	346	24.3	390	1293	5.01

Table A5-2: Welding Parameters 1

File / Weld	WFR_max (m/min)	WFR_med (m/min)	WFR_min (m/min)	WFR_rev (m/min)	T_dwell (ms)	Iarc_max (Amps)	Tarc_max (ms)	Iarc_ramp1 (Amps/ms)	Iarc_med (Amps)
W9050	18	14	20	30	1.0	375	4.0	100	335
W9065	20	22	36	32	1.0	425	4.0	100	425
W9070	22	25	28	33	1.0	450	4.0	100	450
W9075	24	26	20	35	1.0	490	4.0	100	490
W9085	24	25	20	35	1.0	490	4.0	100	490

Table A5-3: Welding Parameters 2

File / Weld	Tarc_med (ms)	Iarc_ramp2 (Amps/ms)	Iarc_min (Amps)	I_backgr (Amps)	T_wetting (ms)	Isc_max (Amps)	Isc_ramp (Amps/ms)	V_sc (Volts)	V_arc (Volts)
W9050	7.0	100	125	20	0.8	250	100	5.0	15.0
W9065	7.0	100	125	20	0.8	250	100	5.0	15.0
W9070	5.0	100	125	20	0.8	250	100	5.0	15.0
W9075	5.0	100	125	20	0.8	300	100	5.0	15.0
W9085	7.0	100	40	20	0.8	300	100	5.0	15.0

Table A5-4: Comments

File / Weld	Comments
W9050	Low to medium spatter.
W9065	Medium spatter. Good stability and bead shape.
W9070	Medium spatter. Good stability and bead shape. Slightly lower spatter than w9065
W9075	Low to medium spatter. Dip frequency a little low. No evidence of droplet detachment in arcing. Good bead with no edge flash.
W9085	Low to low/medium spatter by reducing Iarc_min, also by reducing Tarc_med to sensible value.

Example 4

Statistics and parameter settings for selected welds:
1.2mm AWS A5.18 ER70S-4 electrode, 35mm CTWD, CO_2 shielding.

Table A6-1: Weld Statistics

File / Weld	Avg wire feed rate (m/min)	Short-cct frequency (Hz)	Stability Index	Mean current (Amps)	RMS current (Amps)	Mean voltage (Volts)	Travel speed (mm/min)	Heat input (J/mm)	Mean dip time (ms)
W9450	11.6	33	0.92	214	247	28.3	390	1085	5.53
W9460	13.2	40	0.92	240	269	27.6	390	1184	5.33
W9465	13.6	41	0.90	243	272	27.9	390	1220	5.38
W9475	13.7	42	0.91	255	275	29.3	390	1306	4.50
W9485	14.7	43	0.86	264	287	28.3	390	1321	5.20
W9495	16.0	39	0.87	265	292	27.9	390	1336	6.43

Table A6-2: Welding Parameters 1

File / Weld	WFR_max (m/min)	WFR_med (m/min)	WFR_min (m/min)	WFR_rev (m/min)	T_dwell (ms)	Iarc_max (Amps)	Tarc_max (ms)	Iarc_ramp1 (Amps/ms)	Iarc_med (Amps)
W9450	18	16	25	30	1.0	375	4.0	100	350
W9460	24	22	30	30	1.0	375	4._	100	350
W9465	26	25	30	30	1.0	375	4.0	100	350
W9475	26	23	30	30	1.0	375	4.0	100	300
W9485	28	25	34	30	1.0	400	4.0	100	350
W9495	31	30	40	35	1.0	450	4.0	100	350

Table A6-3: Welding Parameters 2

File / Weld	Tarc_med (ms)	Iarc_ramp2 (Amps/ms)	Iarc_min (Amps)	I_backgr (Amps)	T_wetting (ms)	Isc_max (Amps)	Isc_ramp (Amps/ms)	V_sc (Volts)	V_arc (Volts)
W9450	7.0	100	100	20	0.8	250	100	5.0	15.0
W9460	7.0	100	100	20	0.8	250	100	5.0	15.0
W9465	7.0	100	100	20	0.8	250	100	5.0	15.0
W9475	11.0	100	100	20	0.8	250	100	5.0	15.0
W9485	7.0	100	150	20	0.8	250	100	5.0	15.0
W9495	5.0	100	150	20	0.8	250	100	5.0	15.0

Table A6-4: Comments

File / Weld	Comments
W9450	Low spatter weld. Runs very well. Very low spatter for 1.2mm wire. Good bead. Low dipping frequency.
W9460	Low spatter. Not as low as w9450, but higher deposition rate & dipping frequency. Good bead shape.
W9465	As for w9460.
W9475	Low to medium spatter. Nice flat bead, no detachments.
W9485	Low-medium spatter. Developed from w9465. Not quite as stable, but higher deposition rate. More spatter (consistently- no bursts) due to higher Iarc_min. Good welding condition.
W9495	Low to medium spatter with bursts of high spatter (occasional detachment).

Example 5

Statistics and parameter settings for selected welds:

0.9mm AWS A5.18 ER70S-6 electrode, 15mm CTWD, CO_2 shielding.

Table A7-1: Weld Statistics

File / Weld	Avg wire feed rate (m/min)	Short-cct frequency (Hz)	Stability index	Mean current (Amps)	RMS current (Amps)	Mean voltage (Volts)	Travel speed (mm/min)	Heat input (J/mm)	Mean dip time (ms)
W0157	11.8	83	0.82	186	197	17.5	1500	146	5.65
W0171	13.1	77	0.89	191	205	17.7	1500	155	5.83
W0174	14.5	79	0.81	195	209	19.4	1500	173	5.14
W0177	12.0	88	0.79	194	204	17.8	1500	156	5.22

Table A7-2: Welding Parameters 1

File / Weld	WFR_max (m/min)	WFR_med (m/min)	WFR_min (m/min)	WFR_rev (m/min)	T_dwell (ms)	Iarc_max (Amps)	Tarc_max (ms)	Iarc_ramp1 (Amps/ms)	Iarc_med (Amps)
W0157	38	38	38	20	0.25	250	4.0	100	85
W0171	38	38	38	20	0.25	275	4.0	100	85
W0174	38	38	38	20	0.25	275	4.5	100	85
W0177	38	38	38	20	0.25	250	4.5	100	85

Table A7-3: Welding Parameters 2

File / Weld	Tarc_med (ms)	Iarc_ramp2 (Amps/ms)	Iarc_min (Amps)	I_backgr (Amps)	T_wetting (ms)	Isc_max (Amps)	Isc_ramp (Amps/ms)	V_sc (Volts)	V_arc (Volts)
W0157	7.5	100	80	20	0.75	200	200	12.0	18.0
W0171	7.5	100	80	20	0.75	200	200	12.0	18.0
W0174	7.5	100	80	20	0.75	200	200	12.0	18.0
W0177	7.5	100	80	20	0.75	200	200	12.0	18.0

Table A7-4: Comments

File / Weld	Comments
W0157	Low spatter, very good condition.
W0171	Low spatter, very good condition.
W0174	Low spatter, very good condition.
W0177	Low spatter, very good condition.

Example 6

Statistics and parameter settings for selected welds:
0.9mm AWS A5.18 ER70S-6 electrode, 15mm CTWD, Ar-23%CO_2 shielding.

Table A8-1: Weld Statistics

File / Weld	Avg wire feed rate (m/min)	Short-cct frequency (Hz)	Stability Index	Mean current (Amps)	RMS current (Amps)	Mean voltage (Volts)	Travel speed (mm/min)	Heat input (J/mm)	Mean dip time (ms)
W0527	10.2	96	0.65	163	183	16.1	1500	123	3.7
W0531	9.1	83	0.71	161	175	16.4	1500	123	4.75
W0534	10.2	88	0.74	172	206	16.5	1500	134	4.4
W0537	9.3	81	0.72	165	178	15.4	1500	121	5.38

Table A8-2: Welding Parameters 1

File / Weld	WFR_max (m/min)	WFR_med (m/min)	WFR_min (m/min)	WFR_rev (m/min)	T_dwell (ms)	Iarc_max (Amps)	Tarc_max (ms)	Iarc_ramp1 (Amps/ms)	Iarc_med (Amps)
W0527	28	28	28	20	0.25	250	4.0	100	80
W0531	28	28	28	20	0.25	250	4.0	100	80
W0534	30	30	30	20	0.25	250	4.0	100	80
W0537	32	32	32	20	0.25	250	4.0	100	80

Table A8-3: Welding Parameters 2

File / Weld	Tarc_med (ms)	Iarc_ramp2 (Amps/ms)	Iarc_min (Amps)	I_backgr (Amps)	T_wetting (ms)	Isc_max (Amps)	Isc_ramp (Amps/ms)	V_sc (Volts)	V_arc (Volts)
W0527	7.5	100	80	20	0.75	200	200	12.0	18.0
W0531	7.5	100	80	20	0.75	150	200	12.0	18.0
W0534	7.5	100	80	20	0.75	150	200	12.0	18.0
W0537	7.5	100	80	20	0.75	150	200	12.0	18.0

Table A8-4: Comments

File / Weld	Comments
W0527	Low to medium spatter.
W0531	Low to medium spatter.
W0534	Low to medium spatter.
W0537	Low to medium spatter.

Figure 5 is a photograph of weld beads (26, 27) produced using 0.9mm wire. The upper weld 26 was performed using the W1300 parameter set, while the lower weld 27 used the W1215 parameter set.

The deposition rates achieved with 1.2mm electrodes using short-circuiting transfer are comparable to those described in the literature using pulsed spray transfer. The major advantage of short-circuiting transfer is reduced spatter and improved arc stability, with a consequent improvement in "operator appeal". The stability index for each weld was evaluated using the relationship:

$$Stability\ Index = 1 - \frac{Std\ Deviation\ of\ weld\ cycle\ duration}{Mean\ Value\ of\ weld\ cycle\ duration}$$

For CO_2 shielding all welds which were deemed to be suitable had stability indices greater than 0.80. Most welds achieved a stability index between 0.80 and 0.90. Exceptionally stable welds achieve indices up to 0.94, but these results are achieved when operating below 90% of the wire feed speeds listed in Table 1, and are most likely to be achieved at high CTWDs.

Short-circuiting transfer using conventional equipment can be performed up to approximately 9 m/min to obtain reasonable weld quality. Above this, increasing spatter and poor stability rapidly degrade the process. The results in the above table indicate a doubling of the deposition rate, while maintaining process quality.

The frequency of most welds lies in the range of 35 to 96Hz. These dipping frequencies are lower than those achieved by conventional short-circuiting processes (80 to 200Hz). The lower frequencies are a result of the limitations within the process and its control. The first limitation is the dynamic response of the wire feeding system. A finite time is required to change the speed of the electrode, so an upper limit is placed on the rate at which molten droplets can be transferred via surface tension to the weld pool through electrode speed reversal. If the reversal is not achieved during the short-circuit transfer time, the wire tends to stub into the weld pool, and stability is lost. This first limitation is technological rather than fundamental. The second limitation is, however, fundamental to the process itself. As for argon-based shielding gases, there exists a relationship between the arcing

pulse current I_p and pulse time t_p for which droplets will be produced and ejected from the electrode. While this is a desirable feature for pulsed spray transfer in argon based gases, it is undesirable for short-circuit transfer in CO_2, since free flight transfer is to be avoided. Figure 6 shows the experimentally determined value of this relationship for a 0.9mm ER70S-6 electrode at a CTWD of 12mm. The relationship is expected to be influenced by changes in electrode preheating. The relationship in Figure 6 is approximated by:

$$I^2 t \approx 2116\,(\mathrm{A}^2 s)$$

The data points in Figure 6 were determined by deliberately operating the process at large current pulse widths during the arcing period, and observing the droplet detachment through the recorded transient voltage waveform. The data points in the figures indicate that there is a very large variation in the detachment time when the process is operated in this manner.

Figure 7 shows the I_p/t_p relationship for a 1.2mm ER70S-4 electrode at a CTWD of 16mm. The relationship in this figure is approximated by:

$$I^2 t \approx 2809\,(\mathrm{A}^2 s)$$

Because of the need to avoid free flight transfer, the current pulse applied during the arcing period must be in the lower left hand region of Figures 6 and 7. This means there is an inherent limitation placed on the maximum size of droplet that can rapidly be developed during each arcing period. (A larger droplet can be formed by reducing the current to 100A, say, but this reduces the melting rate and hence deposition rate). When combined with the dynamic limitations of the wire feeding mechanism, a limitation is placed on the maximum average electrode melting rate that can be achieved.

It is worth noting that the "no droplet detachment" region of Figures 6 and 7 is much larger for CO_2 than for argon mixtures. This behaviour is a key advantage for increasing the range of the short-circuiting transfer mode. If the behaviour of CO_2 closely mirrored that of argon mixtures, then the control methodology applied here would not be as effective; as difficulties would be

encountered to develop a sufficiently large droplet during each arcing period to obtain the desired average melting rate.

A secondary factor which places additional restrictions to the process is the arc force generated by high pulse currents. Increasing the current during the arcing period to increase the rate of droplet growth will cause molten material to be ejected from the weld pool. Severe depression of the weld pool causes large oscillations and a deterioration of final bead shape. Increasing the CTWD effectively reduces the magnitude of the current required to produce a given droplet size in a given time, and simultaneously reduces the arc forces acting on the weld pool. This helps explain the higher deposition rates listed in Table 1. The compromise is a reduction in mean current and workpiece heating, but this may be an advantage for welding thin sections at high travel speeds.

In practical applications, the invention is ideally suited to automated systems. The need for rapid and well-controlled reversal of the electrode required that the drive motor is situated close to the contact tip. The torch design is well suitable for robotic systems since the electrode reel can be situated at some distance from the torch, provided that feeding friction is kept low.

It is to be appreciated that alterations and/or additions may be made to the parts and/or embodiments previously described without departing from the spirit or ambit of the invention.

CLAIMS

1. A method of controlling an arc welding system during a welding process having a plurality of welding cycles in which a consumable electrode is advanced towards a workpiece, said method including dynamically regulating a rate of advancement and instantaneous melt rate of said electrode during each welding cycle in response to predetermined events occuring during said welding process.

2. A method according to claim 1 including coordinating said melt rate with said rate of advancement of said electrode.

3. A method according to claim 1 or 2 including controlling a source of power supplied to said consumable electrode.

4. A method according to claim 3 wherein said source of power includes a current waveform.

5. A method according to any one of the preceding claims including monitoring a feedback signal associated with said welding process.

6. A method according to claim 5 wherein said feedback signal includes voltage.

7. A method according to claim 6 wherein said feedback signal includes current.

8. A method according to any one of the preceding claims including sampling in real time conditions associated with said welding process to obtain information for identifying said predetermined events.

9. A method according to claim 8 including processing said information to obtain a first reference signal for regulating said rate of advancement of said electrode.

10. A method according to claim 8 or 9 when appended to claim 2 including processing said information to obtain a second reference signal for controlling said melt rate of said electrode.

11. A method according to any one of the preceding claims wherein said welding process uses a shielding gas.

12. A method according to claim 11 wherein said shielding gas includes CO_2.

13. A method according to any one of the preceding claims wherein said welding system operates in a dip transfer mode wherein each welding cycle includes an arcing phase during which said electrode is spaced from said workpiece and an arc is generated across said space, said arc being operative to form a molten droplet on the end of said electrode, and a short circuit phase during which said electrode is in contact with said workpiece, each welding cycle changing from said arcing phase to said short circuit phase on contact of said molten droplet with said workpiece, and changing from said short circuit phase to said arcing phase after rupturing of a bridge of molten material formed between said electrode and said workpiece.

14. A method according to claim 13 including conditioning the welding system to form a molten droplet on the electrode end during the arcing phase which has a diameter greater than the diameter of the electrode, and causing the droplet to detach from the electrode after the molten droplet has come into contact with the workpiece to thereby ensure a short circuit and arcing phase occurs in each welding cycle.

15. An arc welding system including a power source, a control unit and means for advancing a consumable electrode towards a workpiece during a welding process, said consumable electrode being energized by said power source to cause said electrode to supply molten material to said workpiece, wherein said means for advancing is controlled by said control unit to dynamically regulate a rate of advancement of said electrode in response to predetermined events occurring during said welding process.

16. A welding system according to claim 15 wherein said power source is controlled by said control unit in response to said predetermined events to control an instantaneous melt rate of said electrode.

17. A welding system according to claim 16 wherein said control unit is adapted to coordinate said melt rate with said rate of advancement of said electrode.

18. A welding system according to any one of claims 15 to 17 including means for obtaining a feedback signal associated with said welding process.

19. A welding system according to claim 18 wherein said feedback signal includes voltage.

20. A welding system according to claim 19 wherein said feedback signal includes current.

21. A welding system according to any one of claims 15 to 19 wherein said control unit is adapted to sample in real time conditions associated with said welding process to obtain information for identifying said predetermined events.

22. A welding system according to claim 21 wherein said control unit is adapted to process said information to obtain a first reference signal for regulating said rate of advancement of said electrode.

23. A welding system according to claim 21 or 22 when appended to claim 15 wherein said control unit is adapted to process said information to obtain a second reference signal for controlling said melt rate of said electrode.

24. A welding system according to any one of claims 15 to 23 wherein said welding process uses a shielding gas.

25. A welding system according to claim 24 wherein said shielding gas includes CO_2.

26. A welding system according to any one of claims 15 to 25 wherein said welding system operates in a dip transfer mode over a plurality of welding cycles wherein each welding cycle includes an arcing phase during which said electrode is spaced from said workpiece and an arc is generated across said space, said arc being operative to form a molten droplet on the end of said electrode, and a short circuit phase during which said electrode is in contact with said workpiece, each welding cycle changing from said arcing phase to said short circuit phase on contact of said molten droplet with said workpiece, and changing from said short circuit phase to said arcing phase after rupturing of a bridge of molten material formed between said electrode and said workpiece.

27. A welding system according to claim 26 including means for conditioning said welding system to form a molten droplet on the electrode end during the arcing phase which has a diameter greater than the diameter of the electrode, and means for causing the droplet to detach from the electrode after the molten droplet has come into contact with the workpiece to thereby ensure a short circuit phase occurs in each welding cycle.

28. A method of controlling an arc welding system substantially as herein described with reference to the accompanying drawings and/or examples.

29. A welding system substantially as herein described with reference to the accompanying drawings and/or examples.

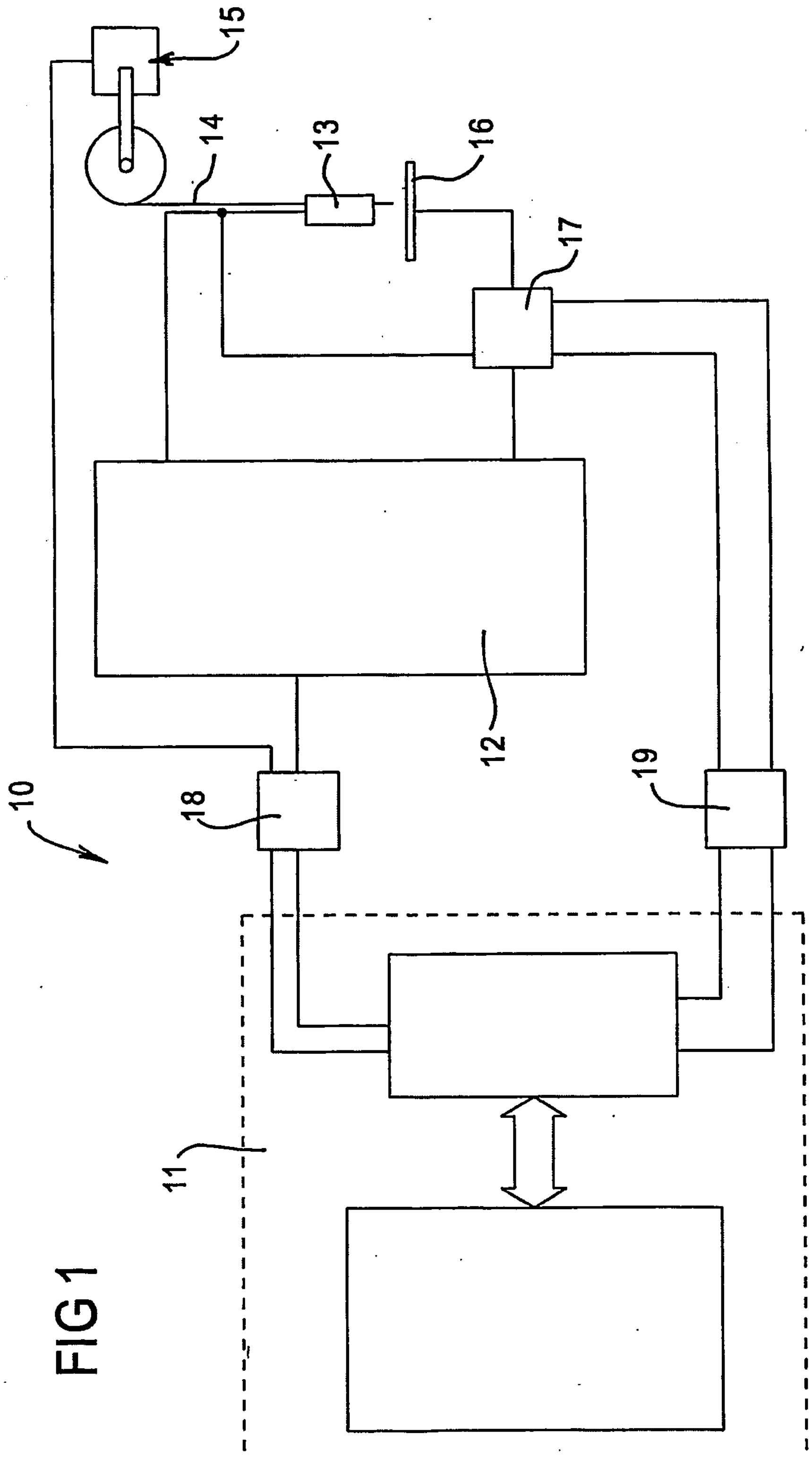


FIG 1

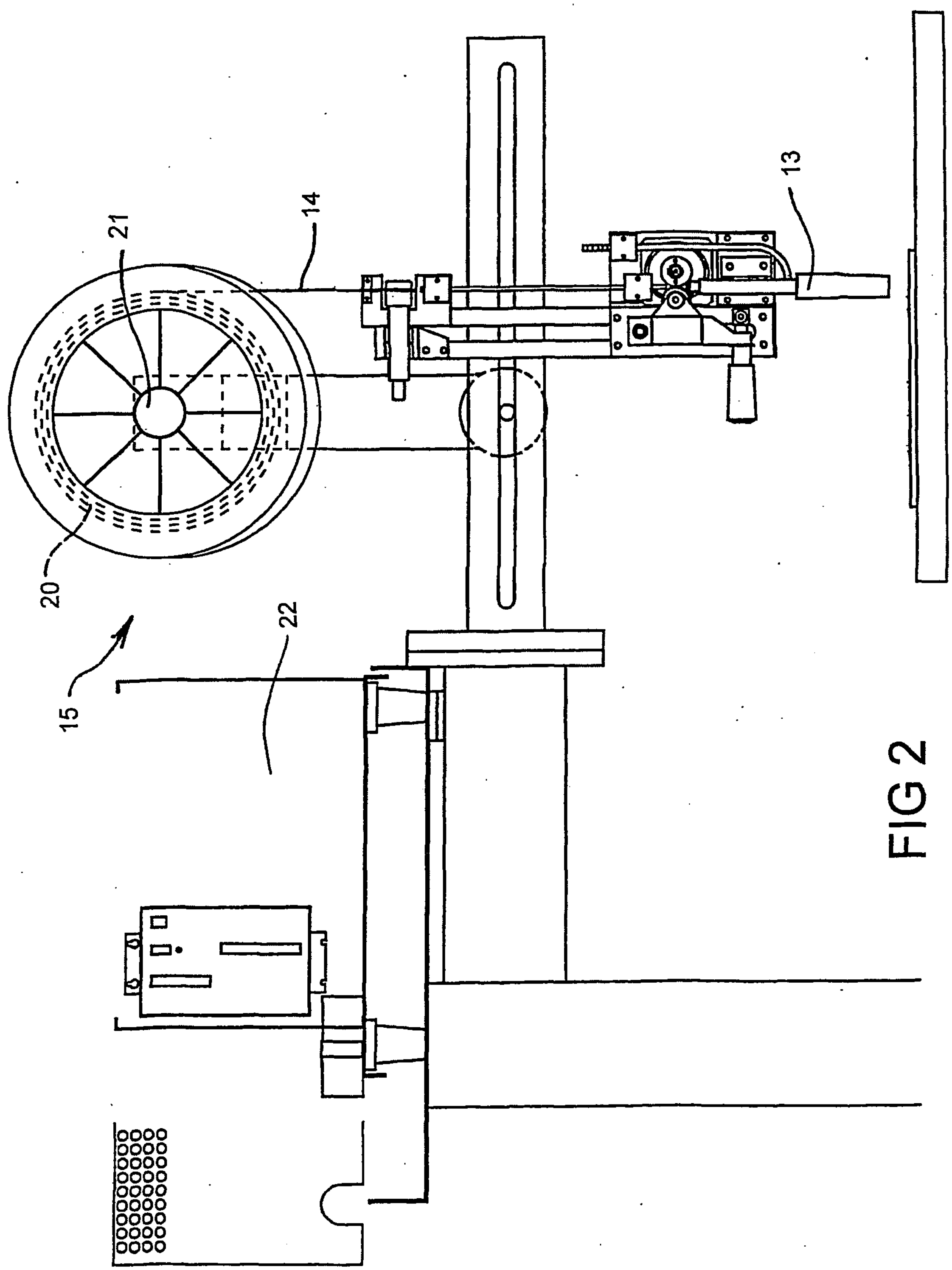
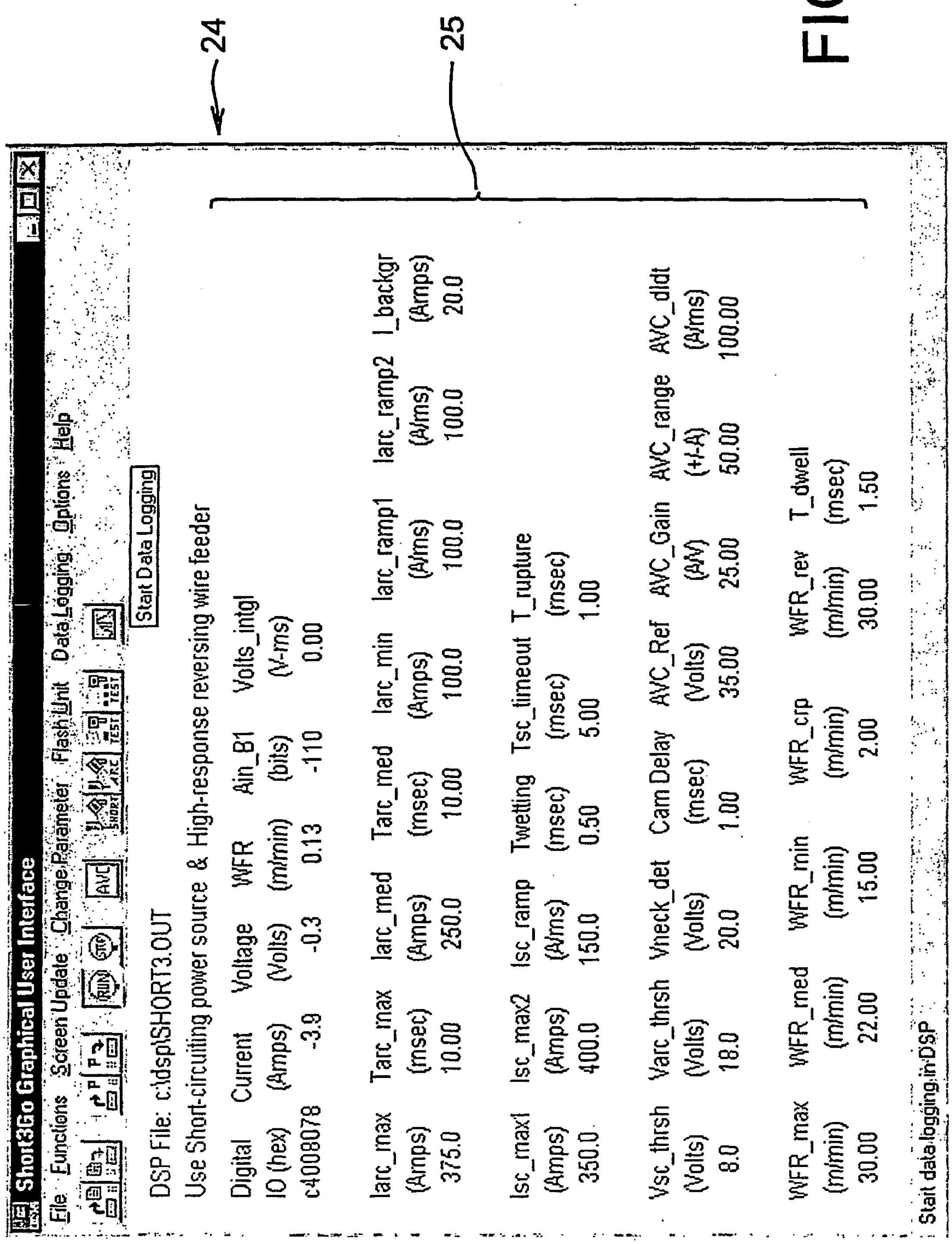


FIG 2



24
25
Short3Go Graphical User Interface
File Functions Screen Update Change Parameter Flash Unit Data Logging Options Help
Start Data Logging
DSP File: c:\dsp\SHORT3.OUT
Use Short-circuiting power source & High-response reversing wire feeder
Digital IO (hex) c4008078
Current (Amps) -3.9
Voltage (Volts) -0.3
WFR (m/min) 0.13
Ain_B1 (bits) -110
Volts_intgl (V-ms) 0.00
Iarc_max (Amps) 375.0
Tarc_max (msec) 10.00
Iarc_med (Amps) 250.0
Tarc_med (msec) 10.00
Iarc_min (Amps) 100.0
Iarc_ramp1 (A/ms) 100.0
Iarc_ramp2 (A/ms) 100.0
I_backgr (Amps) 20.0
Isc_max1 (Amps) 350.0
Isc_max2 (Amps) 400.0
Isc_ramp (A/ms) 150.0
Twetting (msec) 0.50
Tsc_timeout (msec) 5.00
T_rupture (msec) 1.00
Vsc_thrsh (Volts) 8.0
Varc_thrsh (Volts) 18.0
Vneck_det (Volts) 20.0
Cam Delay (msec) 1.00
AVC_Ref (Volts) 35.00
AVC_Gain (A/V) 25.00
AVC_range (+/-A) 50.00
AVC_dI/dt (A/ms) 100.00
WFR_max (m/min) 30.00
WFR_med (m/min) 22.00
WFR_min (m/min) 15.00
WFR_crp (m/min) 2.00
WFR_rev (m/min) 30.00
T_dwell (msec) 1.50
Start data logging in DSP

FIG 3

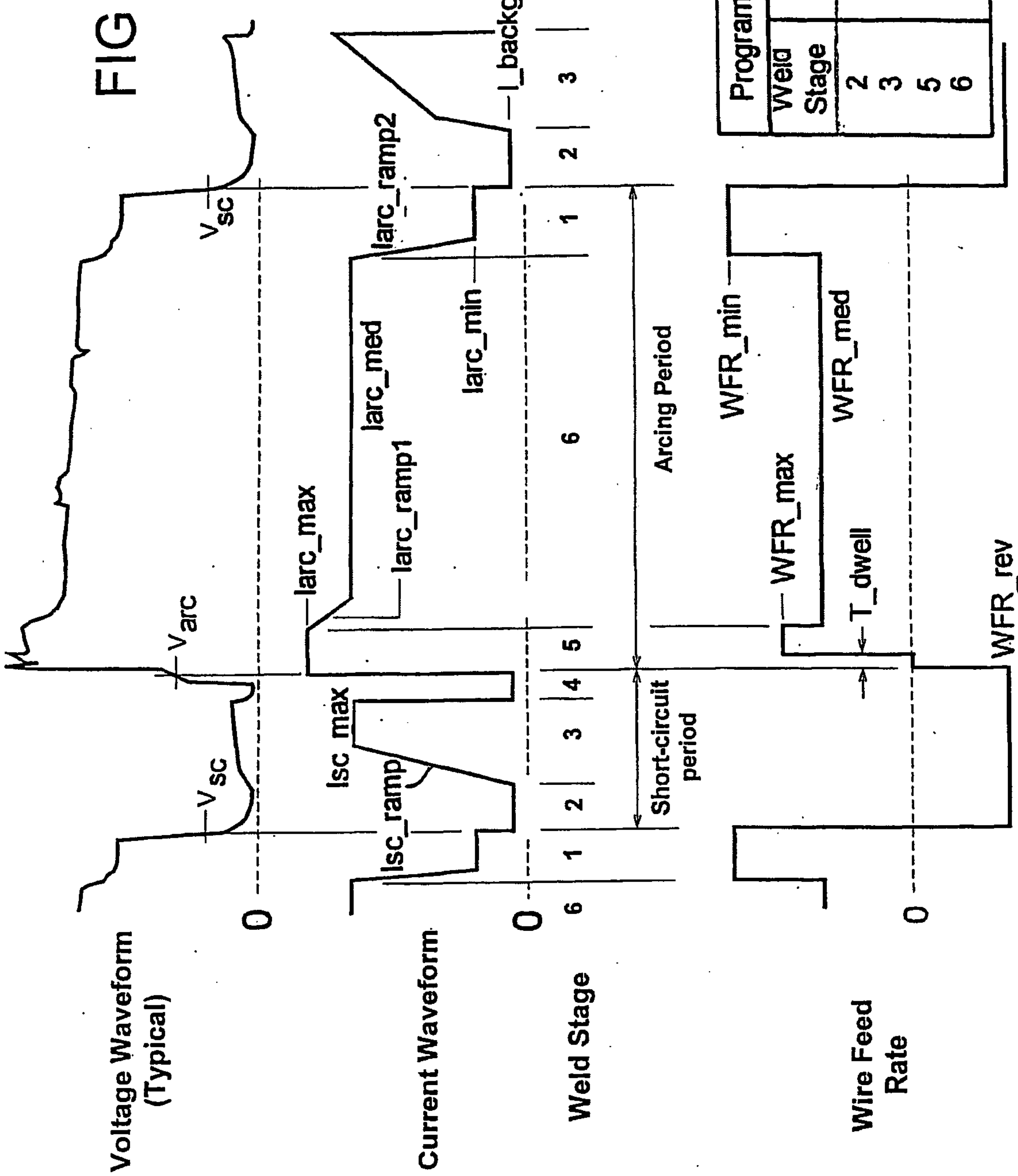


FIG 4

Programmed Times	
Weld Stage	Variable
2	T_wetting
3	Tsc_pulse
5	Tarc_max
6	Tarc_med

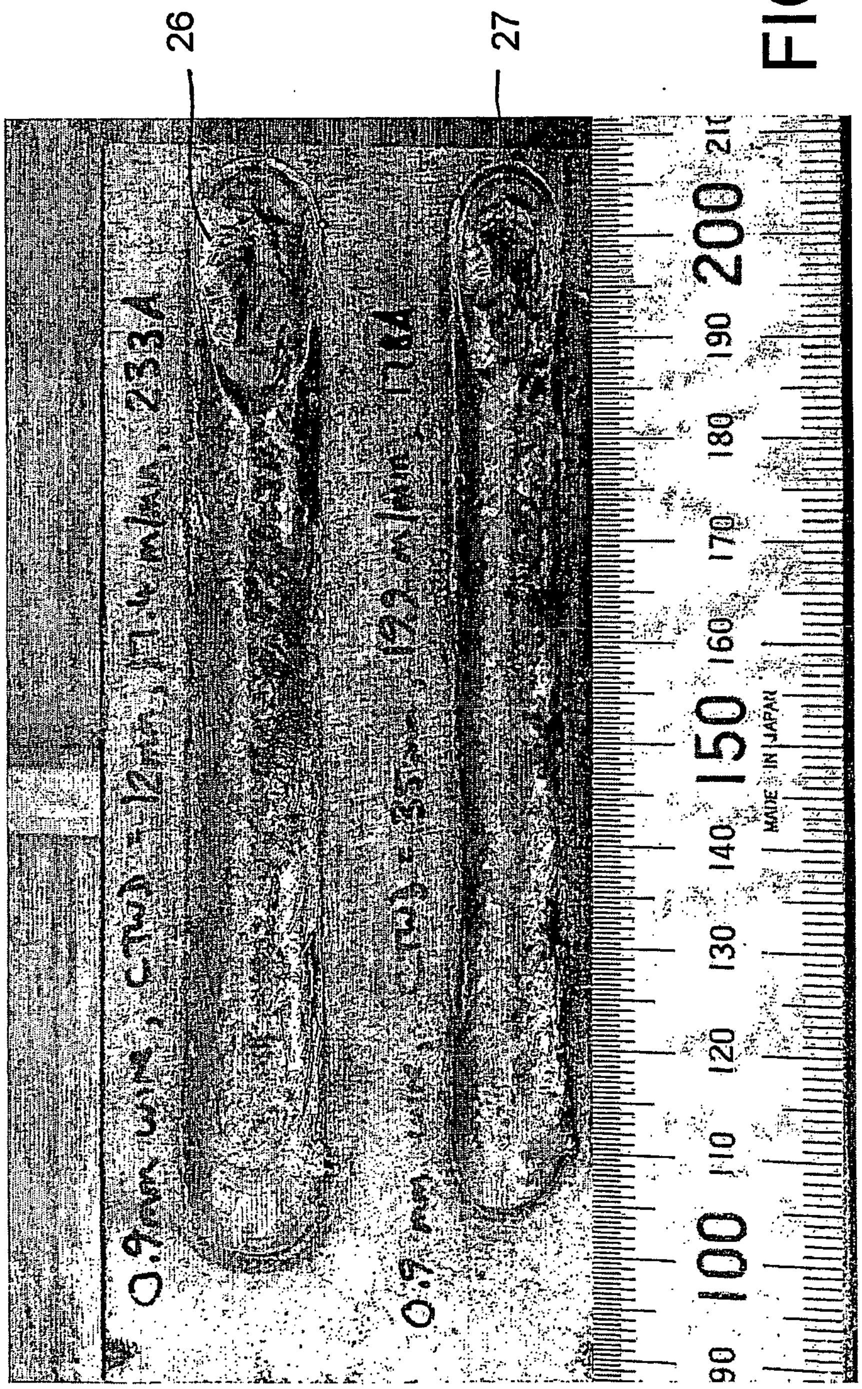


FIG 5

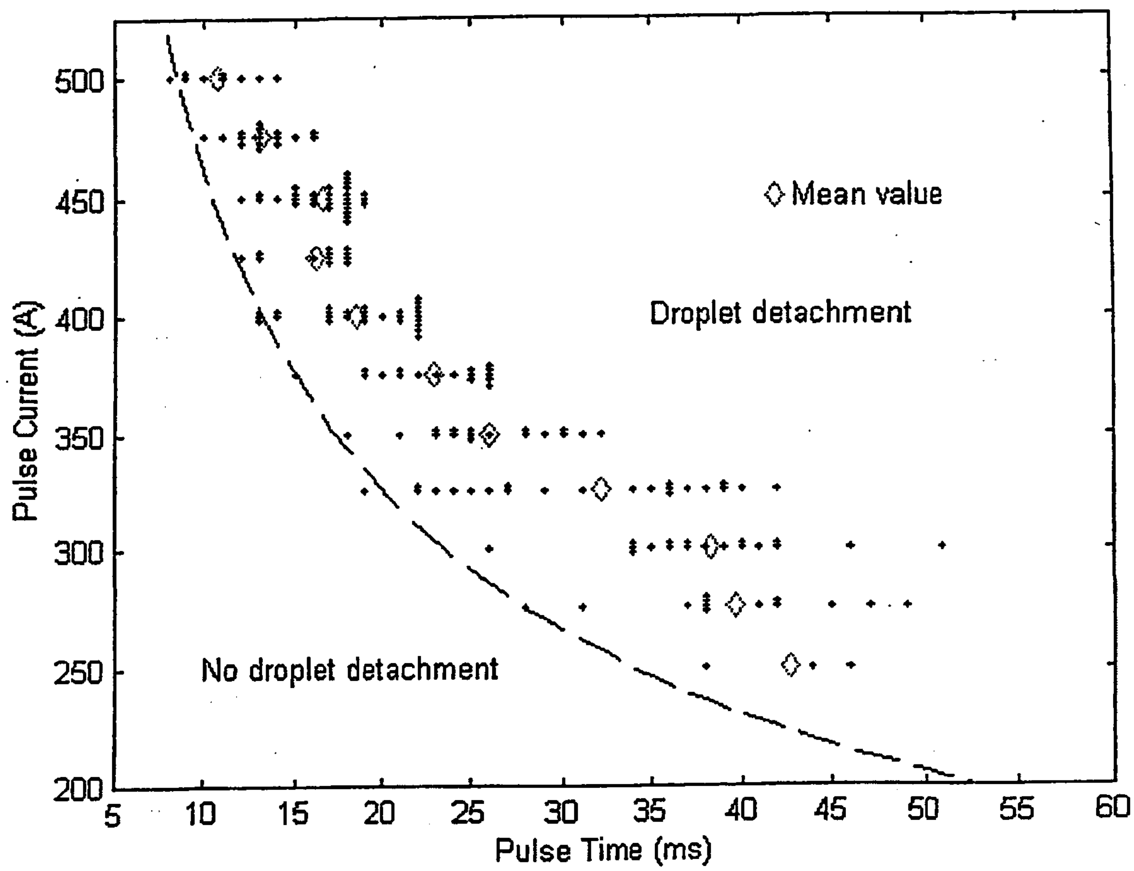

Pulse Current (A)
Pulse Time (ms)
500
450
400
350
300
250
200
5
10
15
20
25
30
35
40
45
50
55
60
◇ Mean value
Droplet detachment
No droplet detachment

FIG 6

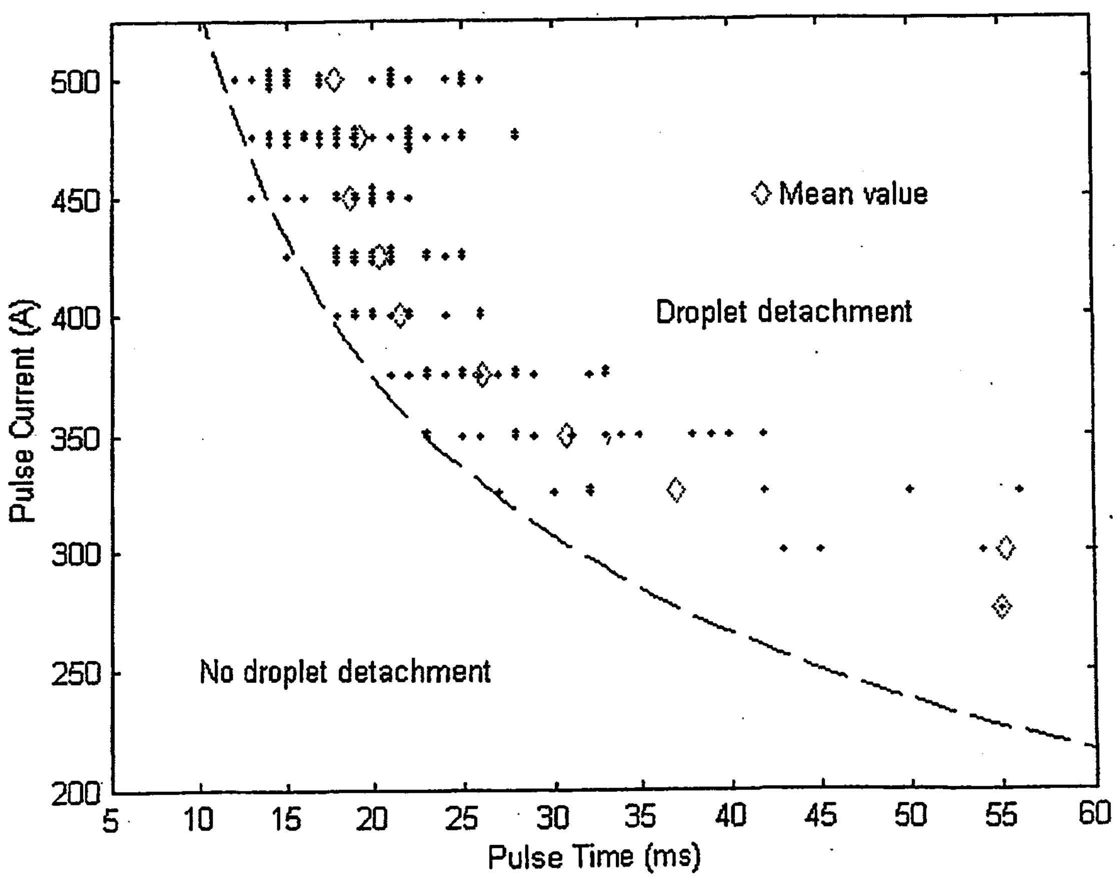

Pulse Current (A)
500
450
400
350
300
250
200
Pulse Time (ms)
5
10
15
20
25
30
35
40
45
50
55
60
◇ Mean value
Droplet detachment
No droplet detachment

FIG 7